Development and Demonstration of Advanced Tooling Alloys For Molds and Dies (CPS#1790)

June 23, 2004

Kevin M. McHugh

IDAHO NATIONAL ENGINEERING & ENVIRONMENTAL LABORATORY
Idaho Falls, ID 83415

Enrique J. Lavernia & Yizhang Zhou

UNIVERSITY OF CALIFORNIA, DAVIS
Davis, CA 92697

Overview

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Project overview
- Energy savings
- Accomplishments
- Commercialization activities
- Future plans

Development and Demonstration of Advanced Tooling Alloys For Molds and Dies (CPS#1790) –Project Summary

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- **Goals**
  - Increase die life for glass manufacture, stamping, forging and die casting by 20% by providing improved die materials and processing.
  - Reduce turnaround time for molds and dies by 20%.
  - Reduce energy consumption associated with the manufacture and heat treatment of dies by 25% by eliminating unit operations in conventional processing, and reducing energy usage during heat treatment.
- **Challenge**: Utilize spray forming and rapid solidification processing to simplify mold making and tailor properties of ferritic mold and die tool steels.
- **Benefits**: Reductions in cost and delivery time for tooling, reduced energy consumption, and potential to improve die performance
- **FY05 Activities**: Benchmarked die microstructure and properties, evaluated material response to conventional heat treatment and aging,evaluated die life, and initiated alloy development work.
- **Partners:** Idaho National Engineering & Environmental Laboratory, University of California–Davis, RSP Tooling LLC, Glass Manufacturing Industry Council, and General Aluminum Manufacturing Co.

Project Team

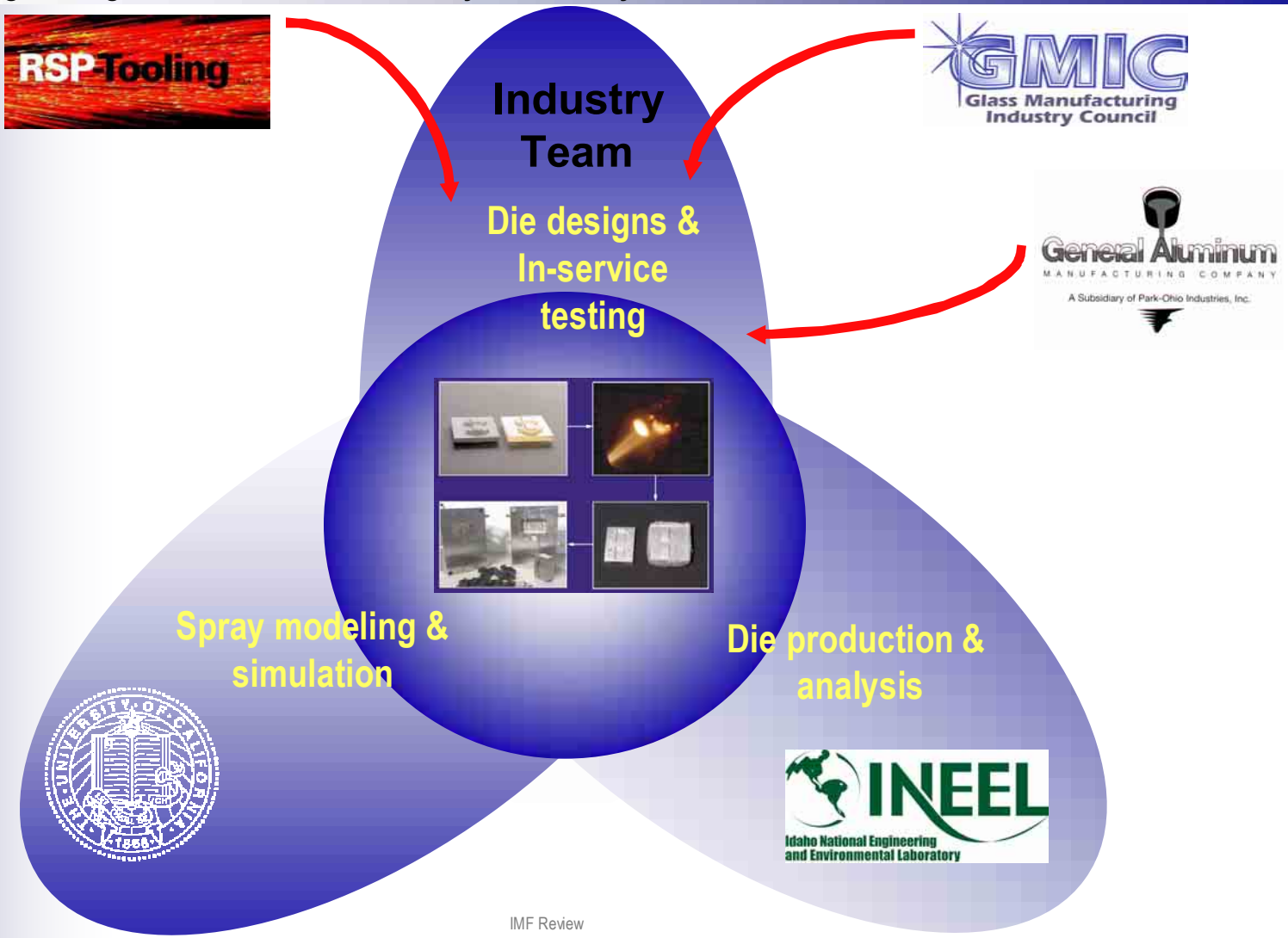
Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH



Development and Demonstration of Advanced Tooling Alloys For Molds and Dies (CPS#1790). Barriers, Pathways, Metrics, Benefits

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Technical Barriers Addressed

- Mold and die manufacture is expensive, time consuming because:
  - Each is custom made to the component's geometry.
  - High accuracy required.
  - Materials difficult to work with.
- Multiplicity of machining, benching, and heat treatment unit operations are labor, energy and capital equipment intensive.

Pathway

- Develop new process for making molds & dies based on spray forming and rapid solidification.
- Benchmark die properties.
- Tailor heat treatment to process.
- Tailor alloys to process.

Metrics

- Compare microstructure and properties with conventional forged dies
- Compare in-service performance with conventional dies of same geometry.
- Compare cost, turnaround time and energy use with conventional dies

Benefits	*Value (est.)*
Energy Savings	19.1 trillion BTU/yr
Cost Savings	Approximately 30%. Increases with die complexity and number of duplicates
Time Savings	Approximately 25%. Increases with die complexity and number of duplicates

RSP Tooling Approach

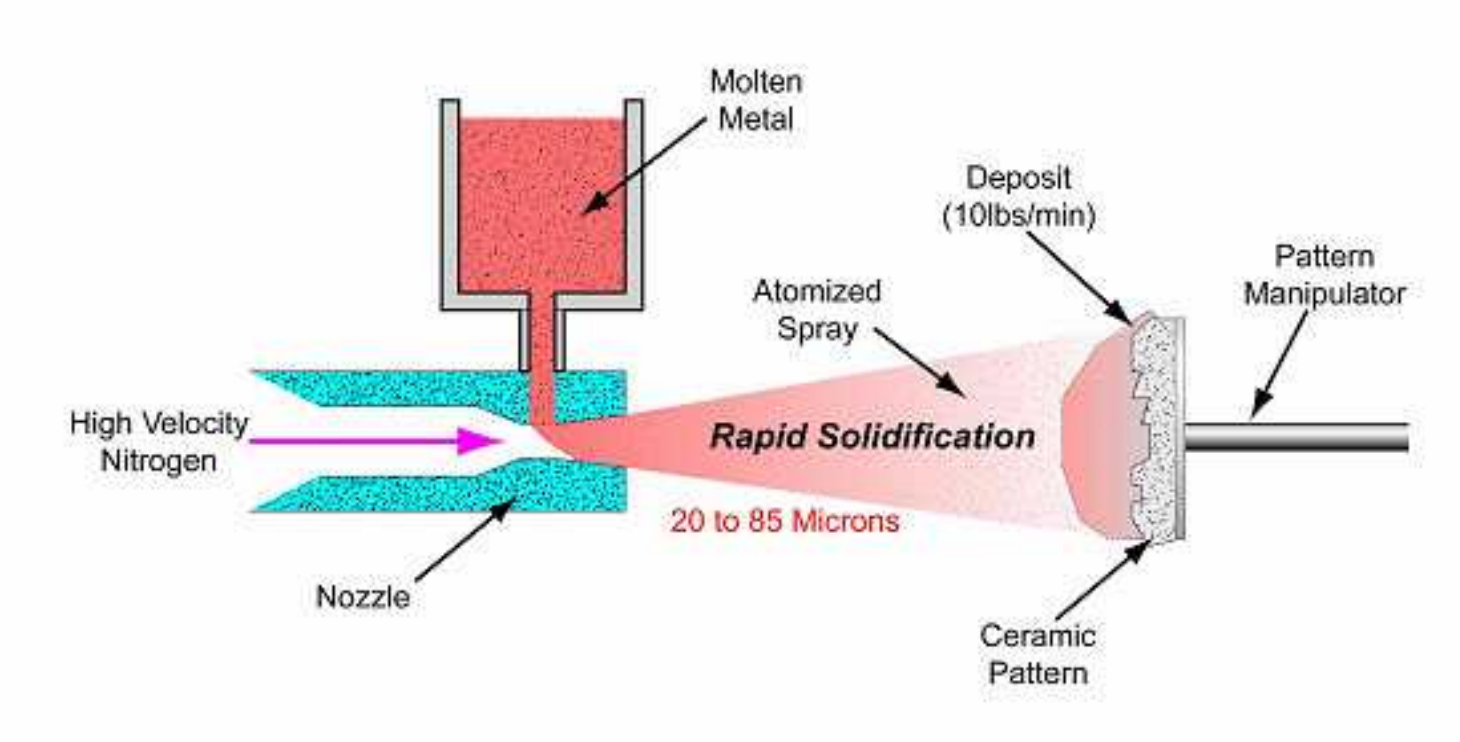
Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

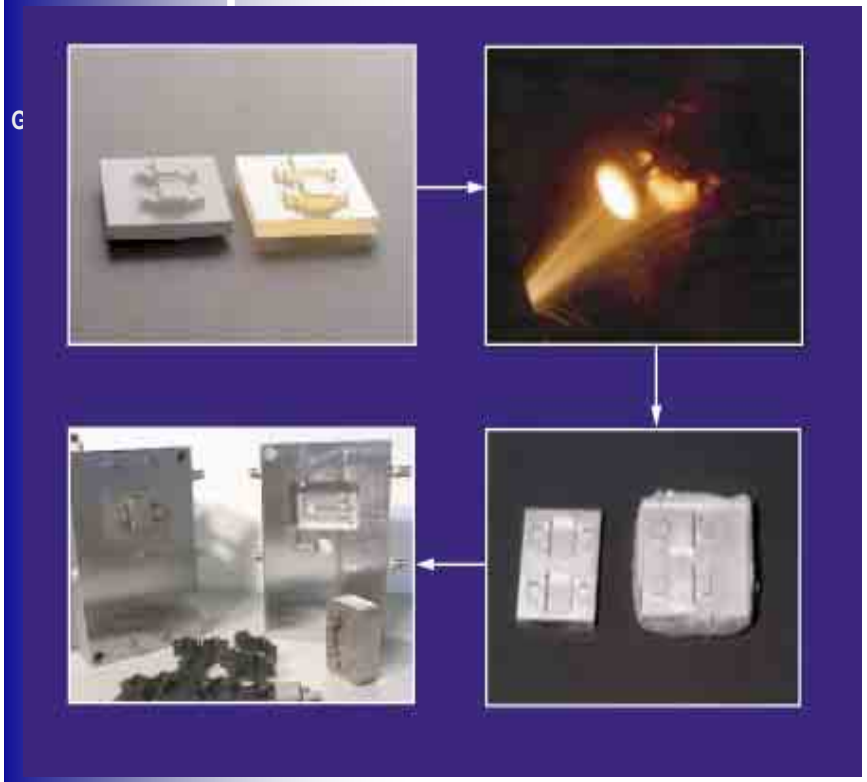
General Aluminum Manufacturing Co.
Conneaut, OH



RSP Tooling – Technology Overview

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:



Processing steps

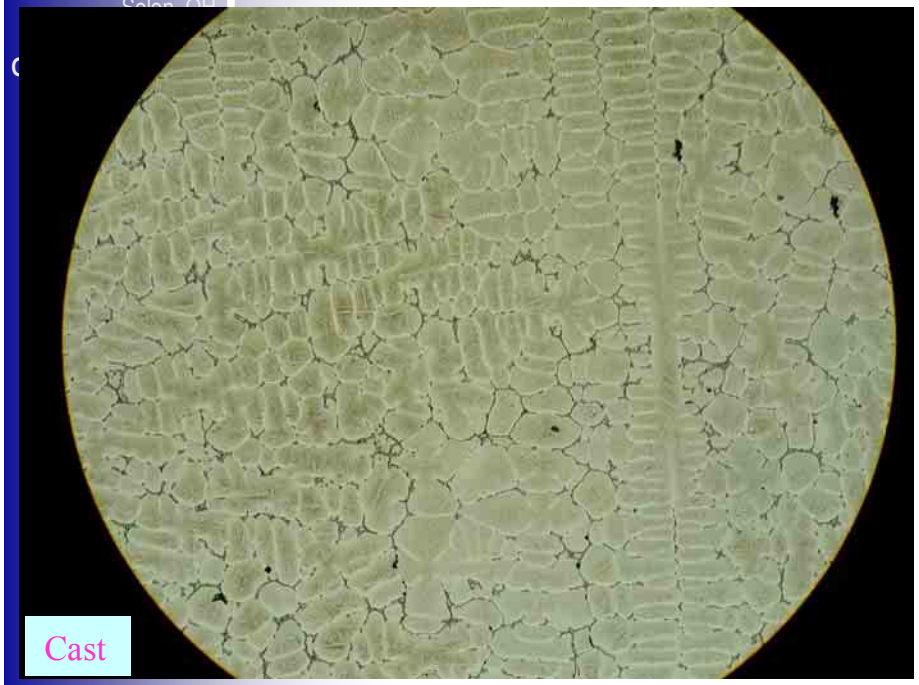
- Molds and dies are used to manufacture nearly all mass produced products. Traditionally, they are machined from a block of steel.
- With RSP Tooling, a spray of molten steel droplets accurately captures the shape and details of a pattern.
- By eliminating machining, grinding, polishing and heat treatment unit operations, RSP Tooling reduces cost and turnaround time for molds and dies.
- R&D 100 Award winner, Energy@23 Award winner, and Federal Laboratory Consortium Award winner.

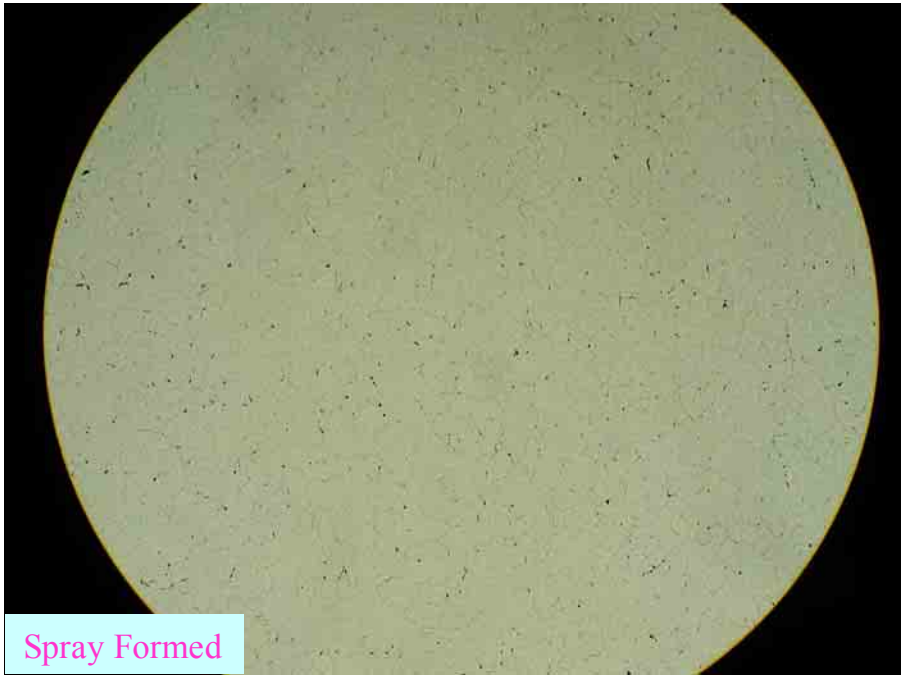
Photomicrographs of A2 tool steel. 50X, etched

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC





Sources of Energy Savings

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Elimination of steel mill unit operations for producing forged plate, rod, bar, etc. suitable for the demands of die-casting, stamping, forging, etc.
- Elimination of many of the machining, grinding, and polishing unit operations necessary to transform the forged steel into molds and dies.
- Potential for die life extension as a result of unique microstructural qualities found in rapidly solidified tool steel.
- The ability to heat treat the tool steel using relatively low temperature artificial aging rather than conventional autenitization/quench/temper heat treatment.

Energy Use

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Processing Step	***Energy Use –*** Conventional Approach (trillion BTU/yr)	***Energy Use –*** New Technology (trillion BTU/yr)	***Energy Savings*** (trillion BTU/yr)
Elimination of steel mill unit operations	10.00	0.33	9.67
Elimination of machining operations	3.75	1.00	2.75
Potential for die life extension	0.92	-	0.92
Die heat treatment	6.70	0.94	5.76
Summary	21.37	2.27	19.10

Electricity is 91.5% of total, natural gas is 4.4% of total, oxygen is 4.1% of total

R&D Methodology

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Industry partners choose tooling alloys to be processed and provide die designs for forming operations such as forging, die casting and glass component manufacture.
- Benchmark microstructure and material properties of dies processed by spray forming.
- Model heat transfer, solidification, and momentum phenomena associated with spray forming of dies.
- Tailor heat treatment and alloy chemistry to rapid solidification processing.
- Industry partners test tools by running them in production, analyzing their dimensional accuracy, surface finish, machinability, weldability, etc.

Accomplishments (INEEL)

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Process Development

- Developed freeze casting technology and procedures for ceramic tool patterns. Evaluated accuracy, turnaround time, and ejection from molds. Evaluated shrinkage of freeze-cast patterns as the composition and concentration of the slurry were varied.
- Adapted uniaxial press to spray forming chamber. Built pattern manipulator for use with press.
- Measured single-phase flow behavior of atomizer as geometry was varied.

Die Manufacture and Industry Analysis

- Provided dies to industry partners for in-service analysis in die casting, permanent mold casting, forging, extrusion, plastic injection molding, and glass manufacture.
- Provided dies to industry partners for dimensional analysis.

Accomplishments (INEEL, cont.)

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Microstructure & Property Analysis of Spray-Formed Dies

- Evaluated microstructure and hardness of spray-formed A2, H13, M2, and modified H13 tool steels.
- Evaluated response of spray-formed H13 to quench rate.
- Evaluated aging response of spray-formed A2, H13, M2, and modified H13 tool steels.
- Evaluated temper response of spray-formed/conventionally heat treated A2 and H13 tool steels.
- Evaluated softening behavior of H13 tool steel at elevated temperature.
- Evaluated tensile properties and impact energy of spray formed, aged, and conventionally heat treated H13 steel.
- Performed Differential Thermal Analysis (DTA) of SF H13.
- Assessed microstructure response of spray-formed H13, M2 and A2 steels to uniaxial compressive forces immediately following deposition.
- Evaluated microstructure and properties of H13 dies made by RSP Tooling, LLC.

Accomplishments (UCD)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Microstructure & Property Analysis of Spray-Formed Dies

- Microstructural characterization of spray-formed H13 and A2 tool steels via optical microscope (OM) scanning electron microscope (SEM), and energy dispersive spectroscopy (EDS).
- Microhardness measurements of spray formed H13 and A2 tool steels.
- Microstructure characterization of Charpy V-notch impact fracture surface of spray formed H13 tool steel.
- XRD analysis of residual stress of as-spray formed A2 steel.
- Residual stress analysis of H13 die sample by neutron diffraction (with Chalk River Laboratories, NRC Canada).

Accomplishments (UCD, cont.)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Microstructure & Property Analysis of Spray-Formed Dies (cont.)

- Strategies have been established for preparation of as-deposited A2 TEM samples (with porosity) using jet polishing.
- Microstructure characterization of A2 produced via deposition plus pressing at INEEL.

Modeling

- Numerical analysis (finite element method) of stress developed during spray forming.
- A numerical model has been developed to predict the microstructural constituents and the size of carbides in as-deposited A2 and H13 tool steels.

Mold and Die Steels Processed

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

H13

- Chemistry:

0.4C-0.35Mn-1Si-5.2Cr-1.3Mo-0.95V

- Classification: Hot Forming
- Applications: Die casting, plastic injection, extrusion, forging.
- Age hardening response: 3 HRC rise to peak age hardness.
- Subtle microstructure changes during aging.

A2

- Chemistry:

1.0C-0.85Mn-0.35Si-5.3Cr-1.1Mo-0.25V

- Classification: Cold Forming
- Applications: Blanking, forming, punching, glass manufacture.
- Age hardening response: 10 HRC rise to peak age hardness.
- Notable microstructure changes during aging.

M2

- Chemistry:

0.85 C-0.30 Mn-0.30 Si-4.2 Cr-5.0 Mo-6.4 W-2.0 V

- Classification: High Speed Steel
- Applications: Form tools, punches, cutting tools.
- Age hardening response: 7 HRC rise to peak age hardness.
- Subtle microstructure changes during aging.

H13-MOD #1

- Chemistry:

0.6C-0.35Mn-1Si-5.2Cr-1.3Mo-2V

- Age hardening response: 3 HRC rise to peak age hardness.
- Subtle microstructure changes during aging.

General Observations

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Rapid solidification provides powerful tool to control carbide formation and growth and grain structure.
- Quench rate influences carbide distribution and nature of matrix phases. Quench rate during deposition more important than post-deposition quench rate.
- Rapidly solidified ferritic tool steels exhibit positive response to aging that is not observed in conventionally-processed material. Both respond similarly to conventional heat treatment
- Unique combination of properties possible with aging that can lead to die-life extension. Aging also eliminates the risk of tool distortion.
- Application of compressive forces immediately after deposition can eliminate porosity and disrupt formation of carbide network in highly-alloyed tool steels.

Examples of industry-conducted production runs in aluminum die casting and steel forging

Idaho National Engineering & Environmental Laboratory - University of California, Davis

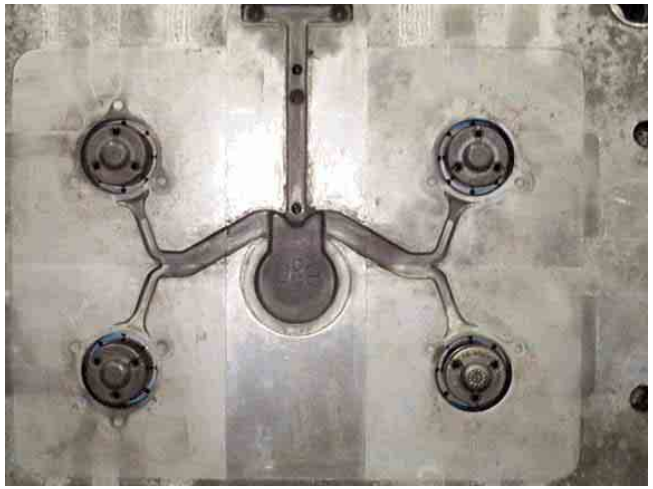
Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Piston cover dies for aluminum die casting (alloy 380).
- Spray-formed H13 dies run side-by-side with conventional machined dies are shown mounted in holding block.
- Spray-formed dies were run in overaged condition.
- Spray-formed dies outlasted conventional dies by 25%



- Spray-formed & conventionally heat treated M2 tool steel forging die (right) used to produce steel gears (left).
- SF die produced suitable number of parts to be classified as a production run. Die life extension not observed. Same failure mode as with machined dies.

Dimensional analysis of spray-formed tools and ceramic patterns

Idaho National Engineering & Environmental Laboratory - University of California, Davis

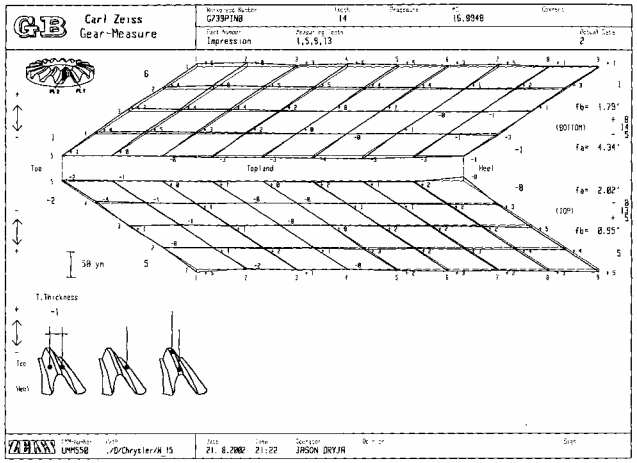
Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Industry partner analyzed accuracy and repeatability of process.
- Slip cast and freeze-cast Al_2O_3 ceramic formulations tested for accuracy.
- Freeze-cast ceramic formulation provided accuracy results that were excellent and consistent.
- Accuracy of spray-formed dies similar to conventional tool-making practices (±0.002”). Excellent repeatability.
- Scaling algorithms under development.



Photomicrographs of H13 tool steel at various cooling rates. 200X, nital etch.

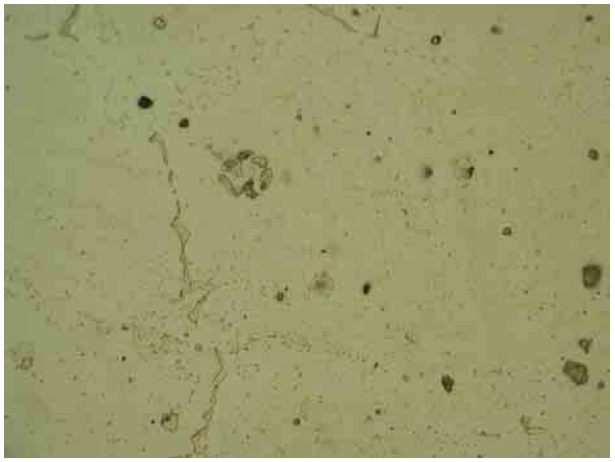
Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

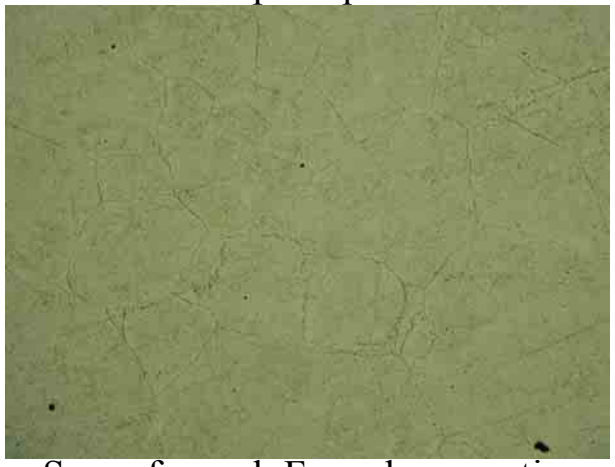
General Aluminum Manufacturing Co.
Conneaut, OH



Cast, polished

Spray formed. Free convection cooled. Deposit/pattern interface

Spray formed. Free convection cooled. Interior



Spray formed. Forced convection cooled. Interior

Photomicrographs of conventionally heat treated H13 and A2 tool steels. 1000X, nital etch.

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Commercial forged H13

Spray Formed H13

Commercial forged A2

Spray Formed A2

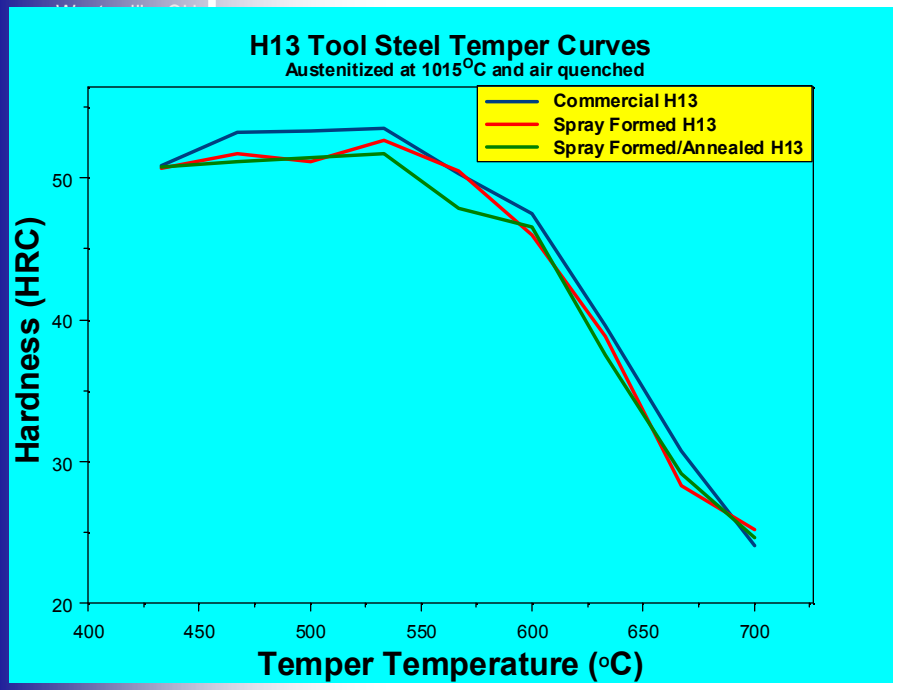
Temper response of austenitized and air quenched H13 and A2 tool steels.

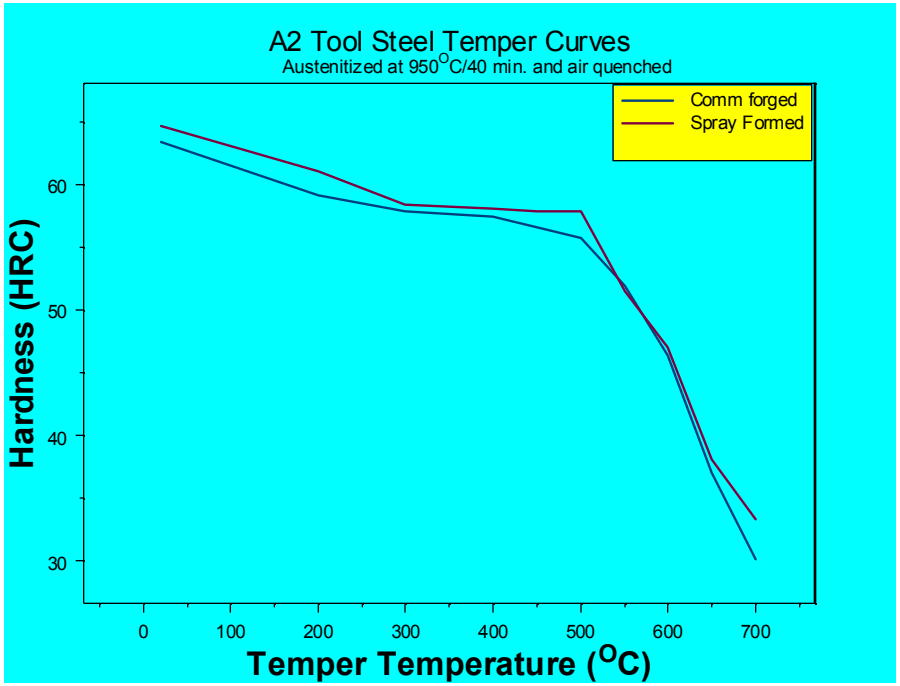
Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council





Hardness response of spray-formed A2, H13, M2 and H13 MOD#1 tool steels to artificial aging

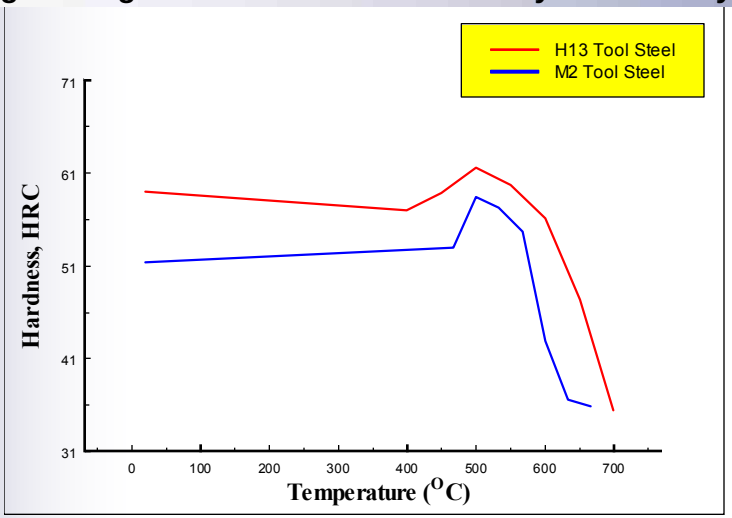
Idaho National Engineering & Environmental Laboratory - University of California, Davis

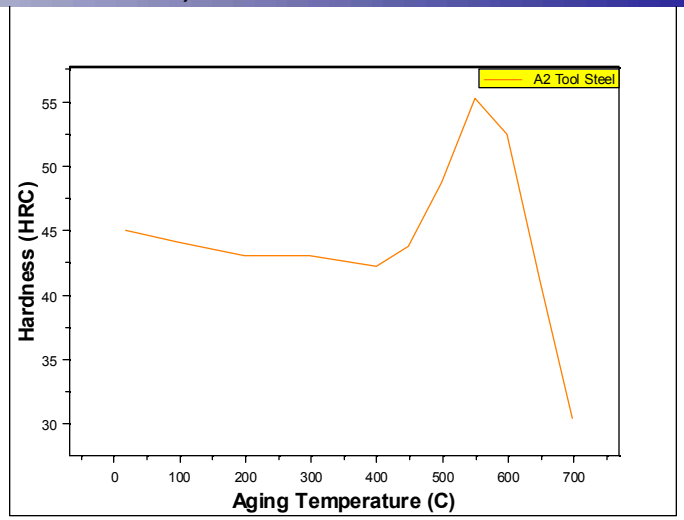
Project Partners:

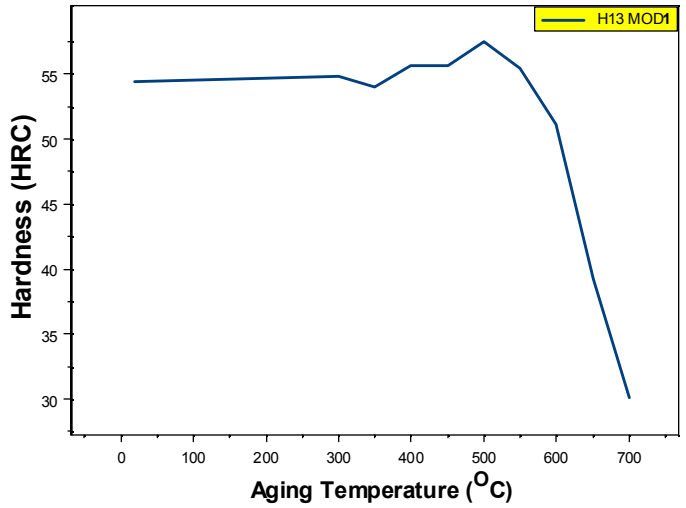
RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH





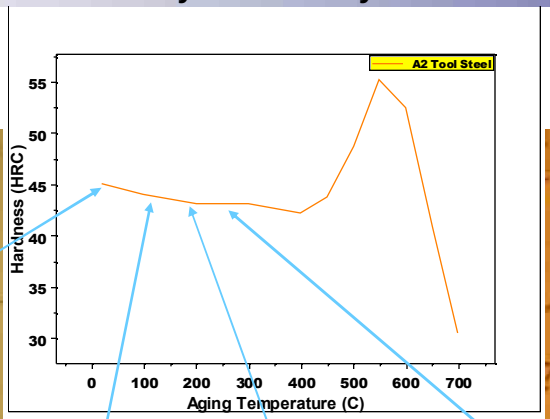


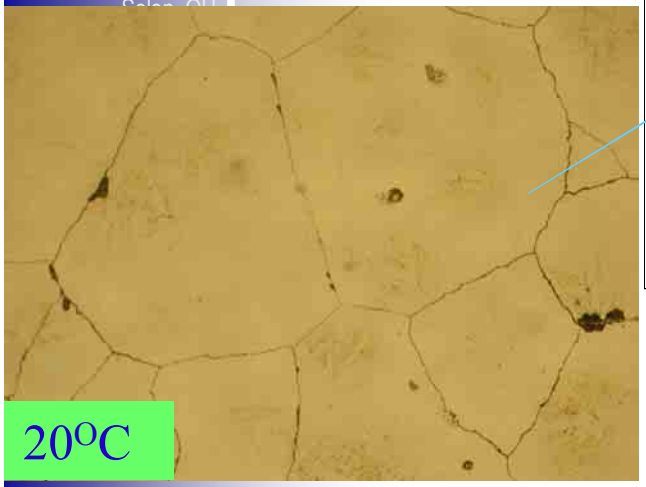
Microstructure transformation in spray-formed A2 during aging, ~500X.

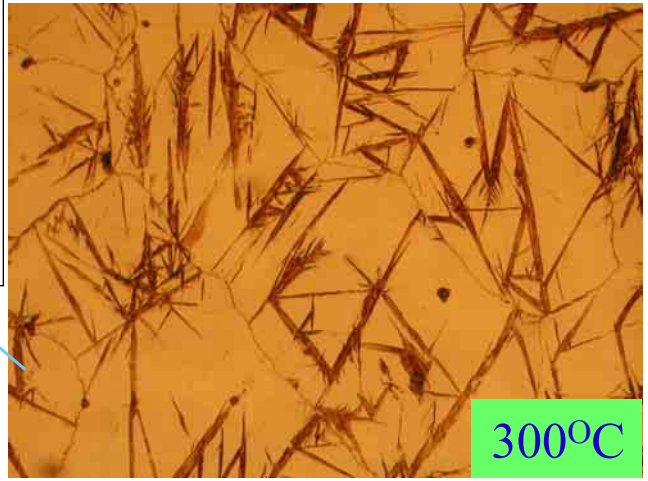
Idaho National Engineering & Environmental Laboratory - University of California, Davis

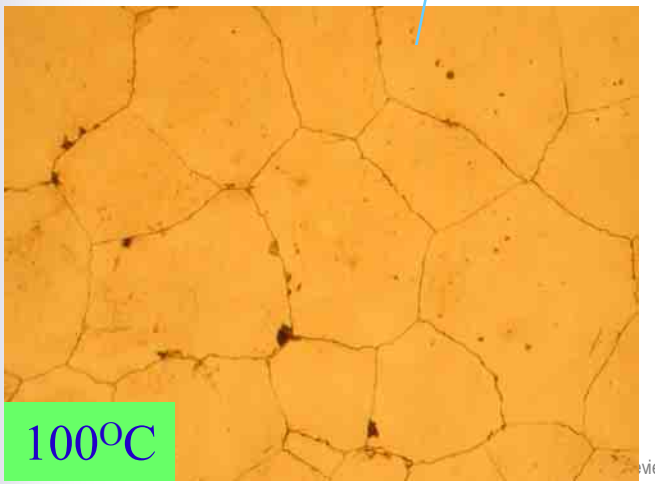
Project Partners:

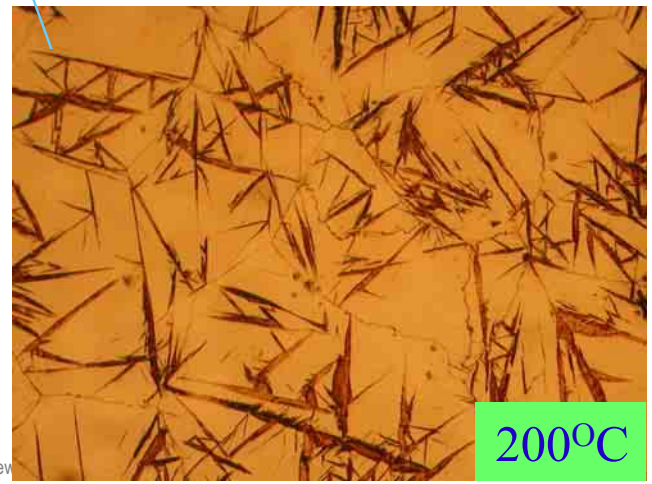
RSP Tooling, LLC









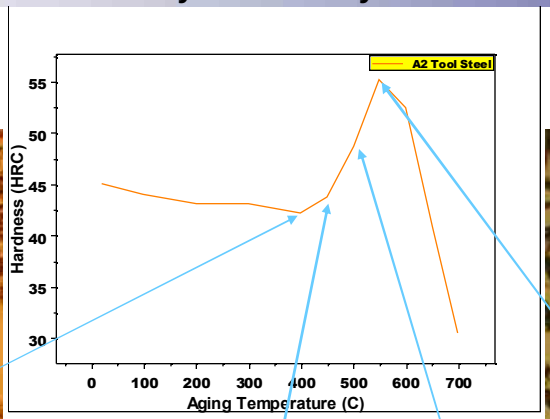


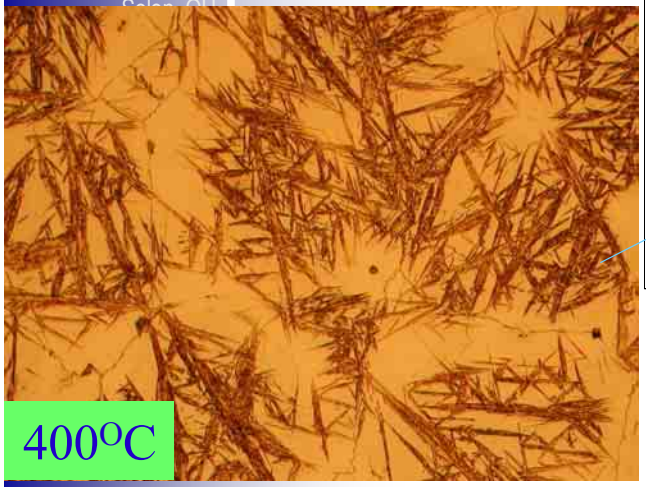
Microstructure transformation in spray-formed A2 during aging, ~500X.

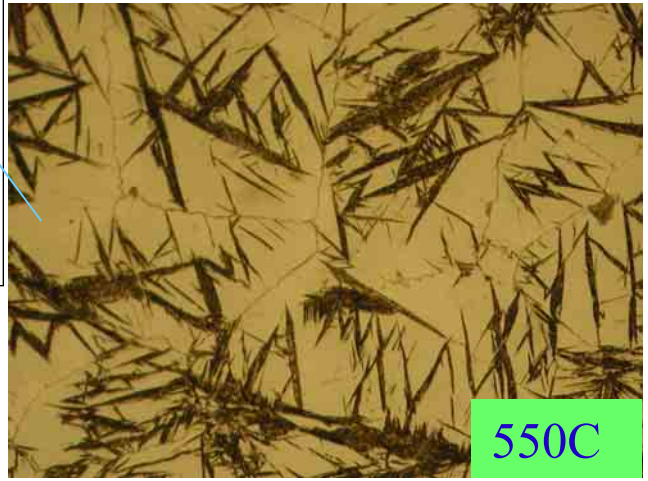
Idaho National Engineering & Environmental Laboratory - University of California, Davis

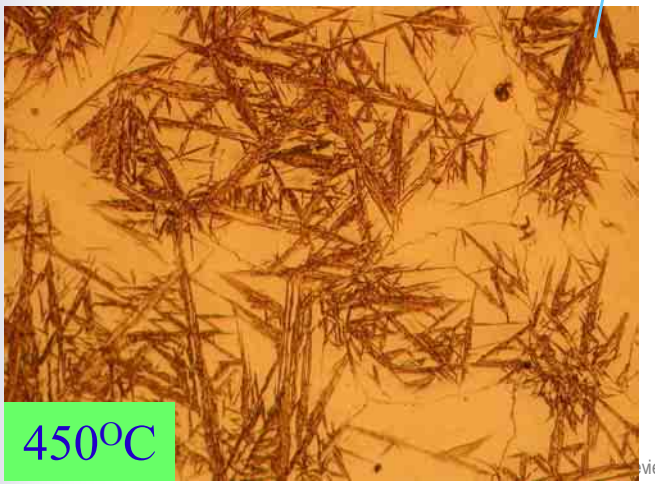
Project Partners:

RSP Tooling, LLC







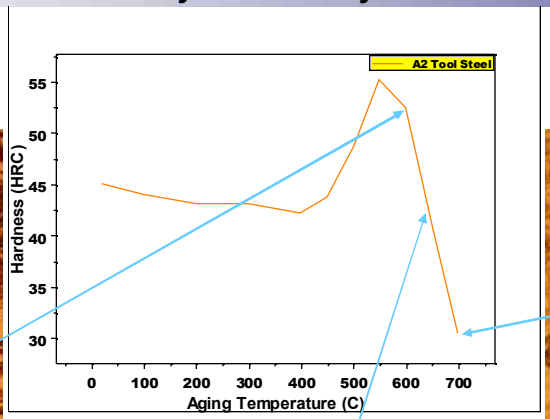


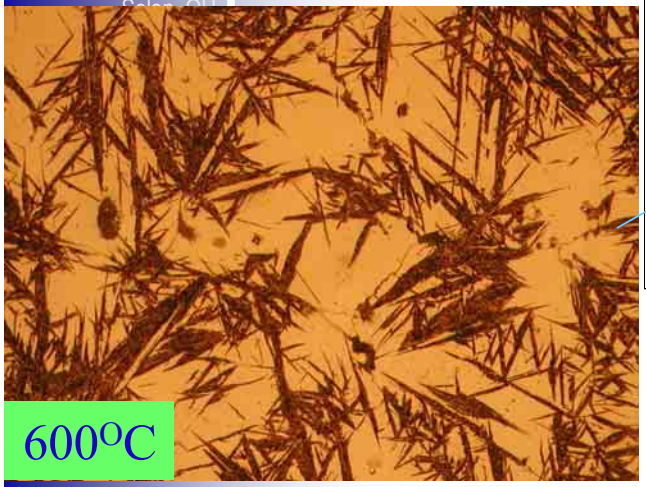
Microstructure transformation in spray-formed A2 during aging, ~500X.

Idaho National Engineering & Environmental Laboratory - University of California, Davis

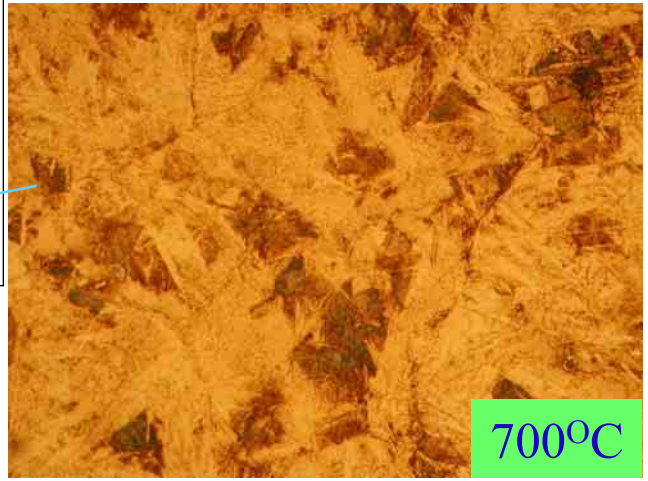
Project Partners:

RSP Tooling, LLC

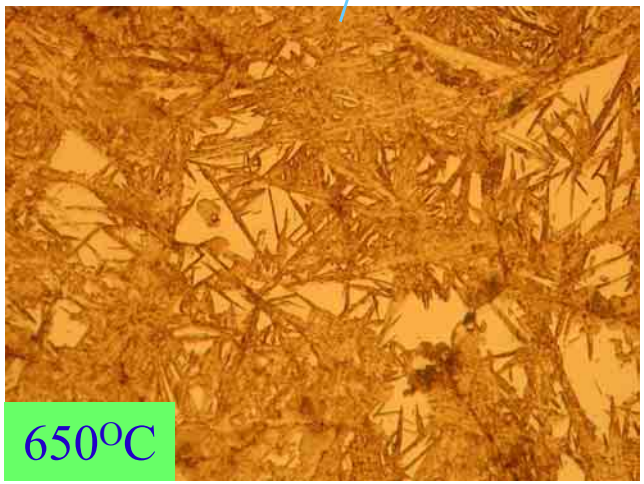




600°C



700°C



650°C

RSP Tooling Process Has Been Commercialized

Idaho National Engineering & Environmental Laboratory - University of California, Davis

- The RSP Tooling process has been commercialized with the formation of RSP Tooling, LLC. Company is located at The Technology House, a rapid prototyping service bureau located in Solon, OH.
- Beta machine, designed/constructed by Belcan Engineering, is operational and selling 7" x 7" inserts.
- Company plans to sell tools and machines, and scale to larger size inserts.

Commercial beta machine

Industry participants with commercial machine at RSP Tooling, LLC Open House

1 Year Ago

(courtesy of RSP Tooling, LLC)

Project Par

RSP Tooling
Sol

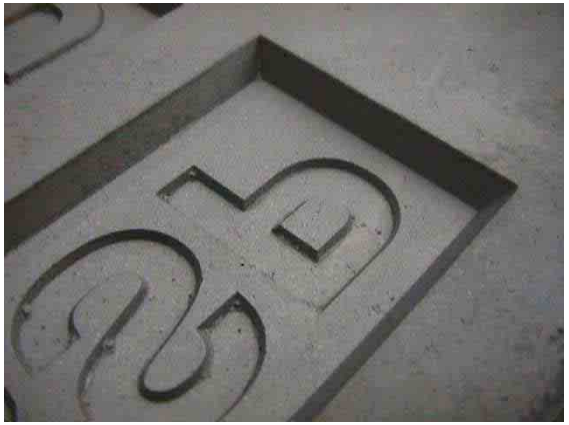
Glass Manufac
Industry C
Westervi

General Alur
Manufacturi
Connea

Hot, Course Spray

Consumables Destroyed

Poor Surface Finish

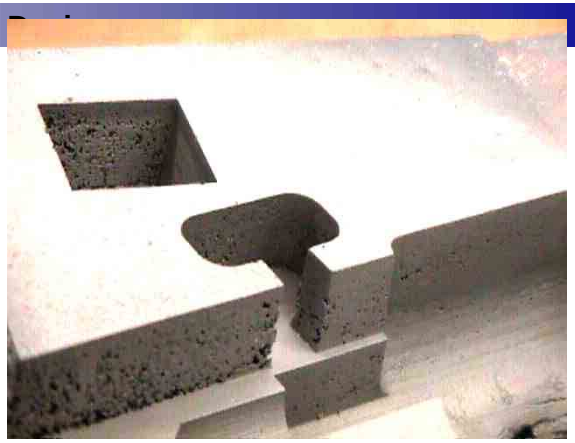


1 Year Ago (cont.)

(courtesy of RSP Tooling, LLC)

Warping

Porosity



Good Surface Finish

Unfilled Standing Feature

6 Months Ago

(courtesy of RSP Tooling, LLC)

Project P

RSP Tooli
Sc

Glass Manufa
Industry
Wester

General Alu
Manufactu
Conne

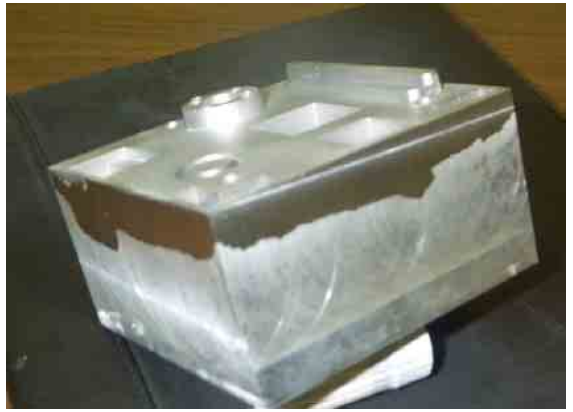
Good Surface Finish

Internal Porosity

Consumables Lasting 3-5 Runs

Deep Extruded Feature

Clad Tooling



Today

(courtesy of RSP Tooling, LLC)

Project

RSP Too

Glass Manu
Industr
West

General A
Manufact
Con

Some Warping

Little or No Porosity

Consumables Lasting 15-20 Runs

Good Surface Finish

Metrics

(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

	Weber (die casting die)	RSP	% Imp	Metaldyne (forging die)	RSP	% Imp
Days	21	16	23%	10	8	20%
Cost	$6578	$5100	22%	$1200	$800	33%

Escalating 2004 Sales

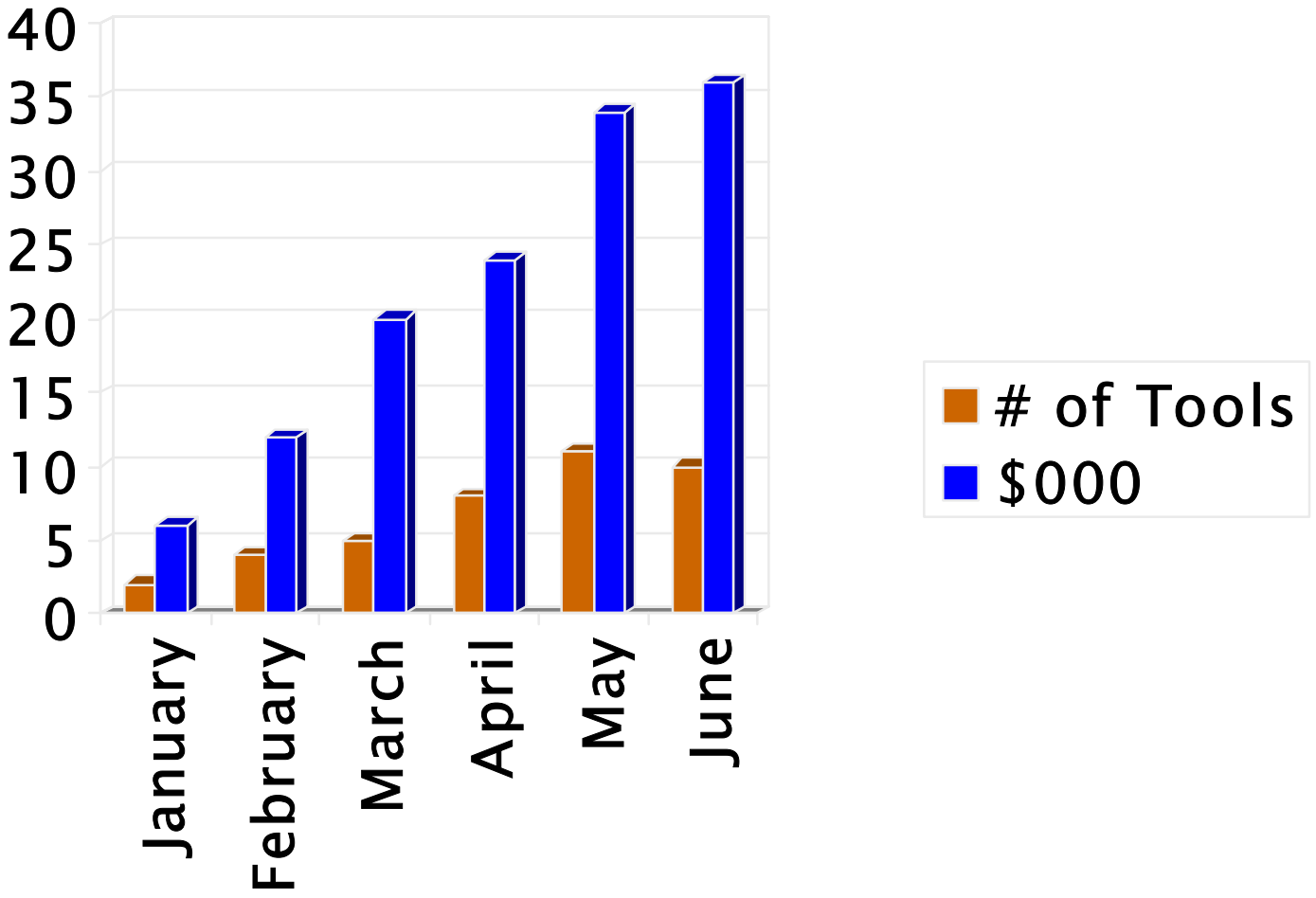
(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH



The Green Machine

(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- A 50# tool uses 50# of steel
  - Normal machine scraps 50# in chips
- Only release to atmosphere is cool nitrogen
  - Normal machine uses cutting fluids
- Significant reduction in energy usage
  - More machines, more costly metal, heat treatment

Industries with tools made on the Beta machine

(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Industry	# of Tools
Forging	12
Plastic Injection Molding	13
Die Casting	8
Extrusion	2
Permanent Mold Casting	3

PM Combustion Molds

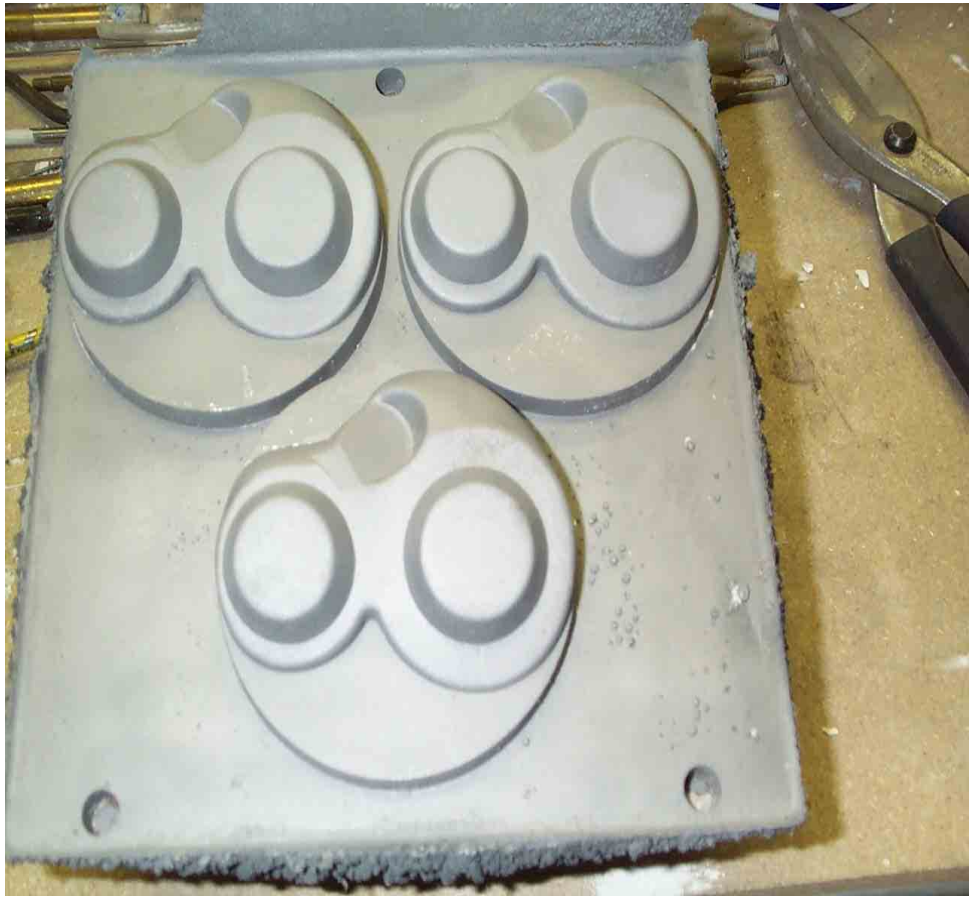
(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH



Die Cast Die

(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

100# Forging Die

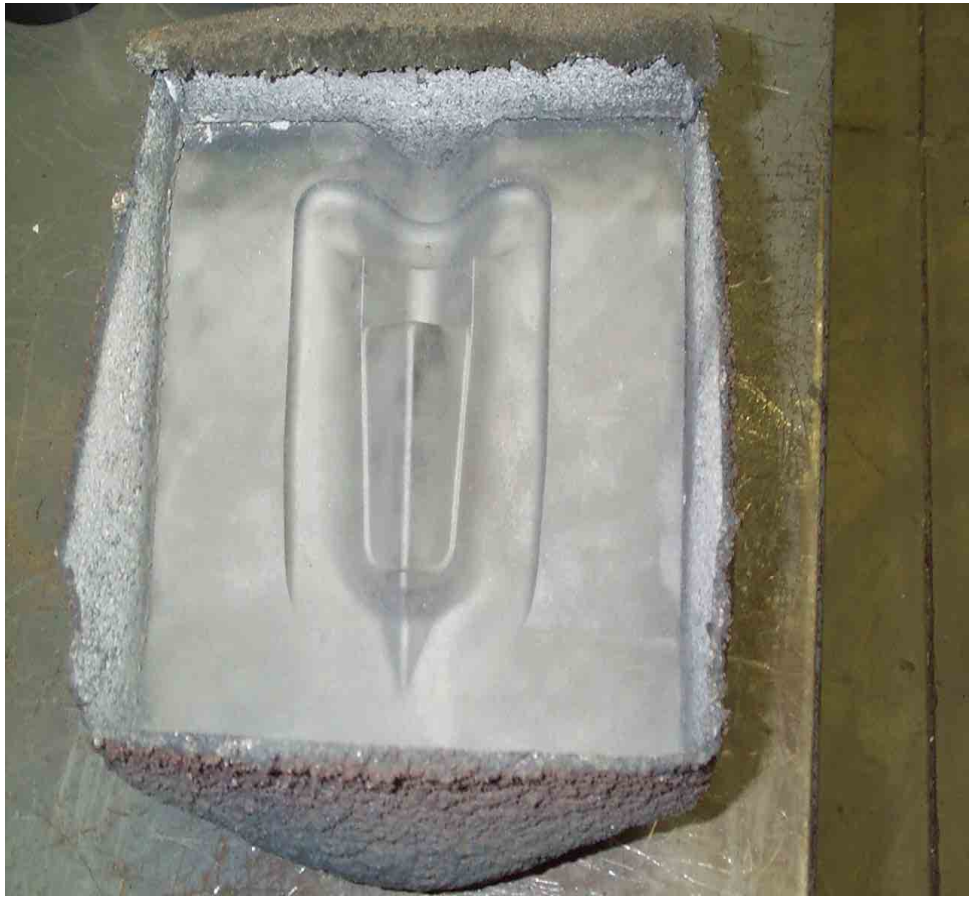
(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH



Plastic Injection Mold

(courtesy of RSP Tooling, LLC)

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

2003-2004 Patents/Presentations/Publications

Idaho National Engineering & Environmental Laboratory - University of California, Davis

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

Patents:

- U.S. Patent 6,746,225 entitled "Rapid Solidification Processing System For Producing Molds, Dies, and Related Tooling" was awarded. Foreign patents have been applied for (allowances in Italy and Canada thus far).

Presentations:

- Kevin M. McHugh, "Production of Molds and Dies Using the RSP Tooling Approach," SDMA 2003 and ICSF V, Bremen, Germany, June, 2003.
- James R. Knirsch, "Rapid High Volume Production Tooling," *Rapid Prototyping and Manufacturing 2003* conference, The Society of Manufacturing Engineers, Dearborn, MI, May, 2003.
- K. M. McHugh, "Rapid Solidification Process (RSP) Tooling for Moldmaking," presented at *Moldmaking 2003* Conference and Expo, Cleveland, OH April 29, 2003.
- An Open House was conducted by RSP Tooling, LLC Feb. 4-7, 2003 in Solon, OH. Approximately 200 people attended. Presentations on RSP Tooling technology were given by INEEL and industry participants in this project.

Publications:

- Kevin M. McHugh, "Use of RSP Tooling to Manufacture Die Casting Dies" *Die Casting Engineer,* July 2004 (in press).
- "Modeling and Experimental Investigation of Spray-Formed H13 Steel Tooling", *Materials Science & Technology 2004*, New Orleans, Louisiana, September 26-29, 2004) (in preparation).
- *James R. Knirsch,* "Reducing Time to Market", *Flow Front* 4 (1), P.15, April, 2004.
- "Rapid-Fire Production Tooling", *Cutting Tool Engineer* P. 96, March 2004.

2003-2004 Patents/Presentations/Publications (cont.)

Publications (cont).

- "New Process Produces Leading-Edge Bimetallic Tooling", *North American Tool & Mold making News,* P. 16, Jan-Feb 2004.
- Kevin M. McHugh and James E. Folkestad, "Production of Molds and Dies Using the RSP Tooling Approach," proceedings of SDMA 2003 and ICSF V, Bremen, Germany, P. 5-123, (2003).
- K. M. McHugh, "Rapid Solidification Process (RSP) Tooling For Moldmaking," proceedings of *Moldmaking 2003* , Cleveland, OH, April 29 – May 1, 2003, P.23 (2003).
- James R. Knirsch, "RSP Tooling," *Advanced Materials & Processes,* 161(1), 62 (2003).
- "Metalworking Executive Rolling Out Speedier Tooling Technology," *Crain's Cleveland Business,* P. 4., February, 2003.
- "New Process Produces Tooling Very Quickly," *Tool and Moldmaking* P. 14, March, 2003.
- "Spray-On Tooling Machine," *American Machinist*, P. 40, April, 2003.
- "Tooling," *Time Compression Technologies,* P. 51, April, 2003.
- James R. Knirsch, "Rapid High Volume Production Tooling," proceedings of *Rapid Prototyping and Manufacturing 2003* conference, paper MF03-226. The Society of Manufacturing Engineers, Dearborn, MI, May, 2003.
- "Lessons From the Gulf War," *Taking Aim* Newsletter, June, 2003.
- "Solon's RSP Ready to Roll," *Crain's Cleveland Business*, December, 2003, P.1.

Future Direction

Project Partners:

RSP Tooling, LLC
Solon, OH

Glass Manufacturing Industry Council
Westerville, OH

General Aluminum Manufacturing Co.
Conneaut, OH

- Continue alloy development work.
- Spray form dies with modified alloys.
- Run dies in production.